

ACI 440.4R-04
(Reapproved 2011)

Emerging Technology Series

Prestressing Concrete Structures with FRP Tendons

Reported by ACI Committee 440



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First Printing
December 2004

Prestressing Concrete Structures with FRP Tendons

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ISBN 978-0-87031-166-6

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Fiber-reinforced polymers (FRPs) have been proposed for use instead of steel prestressing tendons in concrete structures. The promise of FRP materials lies in their high-strength, lightweight, noncorrosive, nonconducting, and nonmagnetic properties. This document offers general information on the history and use of FRP for prestressing applications and a description of the material properties of FRP. The document focuses on the current state of design, development, and research needed to characterize and ensure the performance of FRP as prestressing reinforcement in concrete structures. The

proposed guidelines are based on the knowledge gained from worldwide experimental research, analytical work, and field applications of FRPs used as prestressed reinforcement. The current development includes a basic understanding of flexure and axial prestressed members, FRP shear reinforcement, bond of FRP tendons, and unbonded or external FRP tendons for prestressing applications. The document concludes with a description of research needs.

Keywords: anchorage; bond length; crack; deflection; deformation; development length; ductility; fatigue; jacking stresses; post-tensioning; prestressed concrete; pretensioning; reinforcement ratio; shear; tendon.

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ACI 440.4R-04 became effective September 21, 2004.

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CHAPTER 1—INTRODUCTION

Fiber-reinforced polymer (FRP) composites have been proposed for use as prestressing tendons in concrete structures. The promise of FRP materials lies in their high-strength, lightweight, noncorrosive, nonconducting, and nonmagnetic properties. In addition, FRP manufacturing, using various cross-sectional shapes and material combinations, offers unique opportunities for the development of shapes and forms that would be difficult or impossible with conventional steel materials. Lighter-weight materials and preassembly of complex shapes can boost constructibility and efficiency of construction. At present, the higher cost of FRP materials suggests that FRP use will be confined to applications where the unique characteristics of the material are most appropriate. Efficiencies in construction and reduction in fabrication costs will expand their potential market. FRP reinforcement is available in the form of bars, grids, plates, and tendons. This document examines both internal and external prestressed reinforcement in the form of tendons.

One of the principal advantages of FRP tendons for prestressing is the ability to configure the reinforcement to meet specific performance and design objectives. FRP tendons may be configured as rods, bars, and strands as shown in Fig. 1.1. The surface texture of FRP tendons may vary, resulting in bond with the surrounding concrete that varies from one tendon configuration to another. Unlike conventional steel reinforcement, there are no standardized shapes, surface configurations, fiber orientation, constituent materials, and proportions for the final products. Similarly, there is no standardization of the methods of production, such as pultrusion, braiding, filament winding, or FRP preparation for a specific application. Thus, FRP materials require considerable engineering effort to use properly. Bakis (1993) has outlined manufacturing processes.

FRP tendons are typically made from one of three basic fibers. These fibers are aramid, carbon, and glass. Aramid fibers consist of a semicrystalline polymer known as aromatic polyamide. Carbon fibers are based on the layered graphene (hexagonal) networks present in graphite, while glass generally uses either E-glass or S-glass fibers. E-glass is a low-cost calcium-aluminoborosilicate glass used where strength, low conductivity, and acid resistance are important. S-glass is a magnesium-aluminosilicate glass that has higher strength, stiffness, and ultimate strain than E-glass. S-glass costs more than E-glass, and both are susceptible to degradation in alkaline environments. Table 1.1 gives properties of typical fibers.

The selection of the fiber is primarily based on consideration of cost, strength, stiffness, and long-term stability. Within these fiber groups, different performance and material characteristics may be achieved. For example, aramids may come in low, high, and very high modulus configurations. Carbon fibers are also available with moduli ranging from below that of steel to several multiples of that of steel. Of the several fiber types, glass-based FRP reinforcement is the most expensive and generally uses either E-glass or S-glass fibers.

Table 1.1—Typical fiber properties

	High-modulus carbon (Thornel 2004)	Intermediate-modulus carbon (Torayca 1996)	Standard-modulus carbon (Torayca 1996)	Aramid (Kevlar 1992)	E-glass (Hartman et al. 1994)	S-glass
Tensile strength, GPa	2.1 to 2.4	5.4 to 6.3	3.5 to 4.9	2.9 to 3.0	3.4	4.9
Tensile modulus, GPa	517 to 827	294	230	71 to 112	72.3	86.9
Ultimate strain, %	0.3	1.9 to 2.2	1.5 to 2.1	2.4 to 3.6	4.8	5.7
Mass density, g/cm ³	2.0 to 2.2	1.8	1.8	1.44	2.58	2.46
Diameter, μm	10	5	7	12	3 to 24	6 to 14
Longitudinal CTE, ppm/°C	−1.5	−0.6	−0.4	−4 to −5	5.4	1.6

Note: 1 GPa = 145 ksi; 1 g/cm³ = 62.4 lb/ft³; 1°C = 1.8/°F; 1 μm = 4×10^{-5} in.; CTE = coefficient of thermal expansion.

The resins used for fiber impregnation are usually thermosetting and may be polyester, vinylester, epoxy, phenolic, or polyurethane. The formulation, grade, and physical-chemical characteristics of resins are practically limitless. The possible combinations of fibers, resins, additives, and fillers make generalization of the properties of FRP tendons very difficult. Additionally, FRP composites are heterogeneous and anisotropic. Final characteristics of an FRP tendon are dependent on fiber and resin properties, as well as the manufacturing process. Specific details of a particular tendon should be obtained from the manufacturer of the tendon.

1.1—Organization and limitations of document

The emphasis of this document is on flexural members in concrete buildings and bridges pretensioned with aramid or carbon FRP tendons. An FRP prestressing system consists of the tendon and the anchorage. Properties, performance, and overall behavior are dependent on the tendon/anchorage system and on the individual components. Performance of independent elements should be verified by test. Information is provided for bonded and unbonded post-tensioned applications where it is available. Only fully prestressed members are considered, with no attempt being made to address partially prestressed members. In general, to account for the brittle characteristics of FRP, unlike steel, which is ductile, the recommendations herein are conservative. Specific limitations of FRP tendons are addressed and research needs are listed in Chapter 9. The committee feels that this document is relevant to simple spans and to spans made continuous by placing steel reinforcement in the deck of a bridge structure. No recommendations are made for beams made continuous with FRP tendons or for moment-resisting frames where ductility or large deformations are required for seismic loading. The worldwide number of prestressed FRP applications is less than 100 (MDA 2004; IABSE 2003). Most are bridge structures where issues of fire were not considered critical.

1.2—Historical development and use of FRP reinforcement

The concept of using short glass fiber reinforcement in concrete was first introduced in the 1930s but was not developed into long fiber reinforcement for nearly two decades. In the 1950s and 1960s, the U.S. Army Corps of Engineers was sufficiently interested in long glass fibers for reinforcement

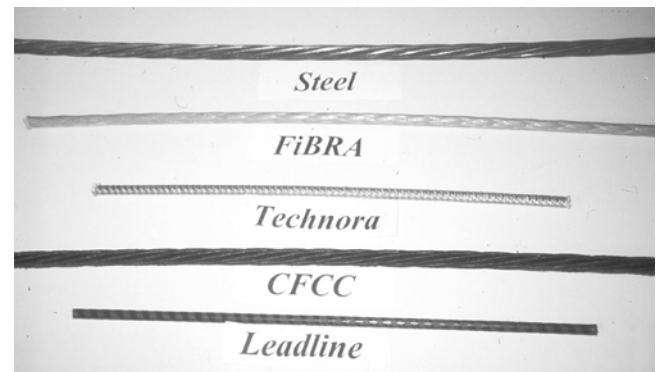


Fig. 1.1—Sample FRP reinforcement configurations.

that a series of comprehensive reports was compiled (Mather and Tye 1955; Pepper and Mather 1959; Wines et al. 1966). Although these reports were generated, research and site applications were limited. In the 1970s, corrosion-induced deterioration of concrete structures, particularly bridge decks, led to a renewed interest in design strategies that would reduce susceptibility of structures to corrosive environments.

In the 1970s, research activities started in Germany on glass FRP-based prestressing tendons. In 1978, a joint venture between German contractor Strabag-Bau and German chemical producer Bayer resulted in glass fiber-reinforced polymer (GFRP) tendons and an anchorage system for post-tensioning applications. These tendons were incorporated in several bridges in Germany and Austria. After various transition stages, however, Strabag stopped its activities in this field in the early 1990s. The National Bureau of Standards (NBS)—now renamed the National Institute of Standards and Technology (NIST)—examined nonmetallic rods for antenna guy wires. In the process, they conducted some of the first research into anchorage of composite rods that became relevant to prestressed concrete application of FRP materials (NBS 1976).

Interest in the corrosion-resistant properties of nonmetallic bars and tendons continued to grow in the 1980s. In 1983, AKZO, a chemical producer in the Netherlands, and HBG, a contractor, jointly developed aramid fiber reinforced polymer (AFRP) prestressing tendons. In Japan, Nippon also undertook an extensive national program to examine

the use of FRP reinforcement in concrete structures. Around 1980, research and development began in Japan on production techniques for FRP reinforcement and its application to concrete structures. This research and development originally focused on the development of FRP-reinforced concrete members that used FRPs instead of steel reinforcing bars and prestressing tendons. In the United States, a new anchorage was developed for glass fiber tendons (Iyer and Kumarswamy 1988), and the prestressing use of Kevlar™ was investigated (Dolan 1989). Iyer's anchorage was supported financially by the Florida Department of Transportation (FDOT), which funded a major study to investigate the prestressing application of glass fiber tendons for bridge and marine substructures (Sen, Issa, and Mariscal 1992). This research culminated in the first conference to focus on FRP composites for civil engineering applications (Iyer and Sen 1991), and the construction of the first FRP prestressed bridge in Rapid City, South Dakota (Iyer 1993). These and similar efforts led to the development of several commercial tendon systems, many of which are discussed in the proceedings of the First International Symposium for FRP in Reinforced Concrete Structures (FRPRCS-1) (Nanni and Dolan 1993), and in a Japanese Society of Civil Engineers publication (JSCE 1996).

1.3—Design guidelines and technical committees

In 1993, the first design guidelines for FRP-reinforced and prestressed concrete buildings were established by the Japanese Society of Civil Engineers. The Japanese version of the guideline was released in 1995, while the English version (Sonobe et al. 1997) was published in 1997. The Canadian Standards Association has produced two standards—CAN/CSA S6-00 and CAN/CSA S806-02—that contain code provisions for the use of FRP prestressing tendons in bridges and buildings, respectively.

In Europe, unified design guidelines for FRP reinforcement are under development. A task group with this aim was established at the end of 1996, within the former CEB (Euro-International Concrete Committee). In December 1997, a 4-year training and mobility of researchers network project, titled “Development of Guidelines for the Design of Concrete Structures, Reinforced, Prestressed or Strengthened with Advanced Composites,” started. This so-called “ConFiber-Crete Network” was comprised of 11 teams from nine different European countries.

Since the merger of CEB and FIP (*Federation Internationale de la Précontrainte*), this task group has been integrated in the new *fib* (*Federation Internationale du Béton*). Task Group 9.3 of *fib* Commission 9 is charged with developing design guidelines for concrete structures reinforced, prestressed, or strengthened with FRP, based on the design format of the CEB-FIP Model Code and Eurocode 2 (*fib* TG9.3). Recent activities in Europe have been summarized by Matthys and Taerwe (2001).

The American Society of Civil Engineers (ASCE) established a standards committee to address stand-alone FRP products. The Transportation Research Board (TRB) has formally established Committee A2C07 to examine the use of FRP in bridge structures. Other societies, including the Society for

the Advancement of Material and Process Engineering (SAMPE) and the Market Development Alliance (MDA) of the FRP Composites Industry, have been active in the area of FRP for construction use.

1.4—Research efforts

Early development work on prestressing with FRP was carried out at the South Dakota School of Mines by Iyer who developed the first prestressing anchorage in the late 1980s. The first glass fiber prestressed bridge built in the United States was in Rapid City, South Dakota, in 1990. Other research was carried out at the University of South Florida, Florida Atlantic University, and the Florida Department of Transportation (Sen, Issa, and Mariscal 1992). Studies included static and fatigue testing of beams and half-scale bridges, durability studies, and full-scale testing of piles. All three materials—aramid, carbon, and glass—were evaluated.

Work relating to FRP prestressing in the United States has been documented by Dolan (1999). Much of the research on FRP reinforcement in the United States has been conducted by individual investigators at the University of Arizona (Eshani, Saadatmanesh and Nelson 1997), the University of Michigan (Naaman and Jeong 1995), the Massachusetts Institute of Technology (Triantafillou and Deskovic 1991), Pennsylvania State University (Nanni et al. 1996a,b), South Dakota School of Mines (Iyer et al. 1996), the University of California (Long Beach), West Virginia University (Vijay and GangaRao 2001), the University of Wyoming (Dolan et al. 2000), and Lawrence Technological University (Grace 2000a,b). In 1993, FHWA sponsored research into accelerated aging and standardized testing of FRP materials at Georgia Institute of Technology, Pennsylvania State University, and the Catholic University of America. In 1994, FHWA sponsored research into development of design recommendations for FRP prestressing for bridge girders that led to design specification recommendations for AASHTO (Dolan et al. 2000). Lawrence Technological University has developed a demonstration bridge using external unbonded FRP tendons (Grace 1999).

In Canada, several researchers, mostly within ISIS Canada (Canadian Network of Centers of Excellence on Intelligent Sensing for Innovative Structures), have been investigating applications of FRP prestressing tendons. Work at the University of Manitoba has emphasized carbon FRP tendons and has considered the behavior of prestressed beams under both service and ultimate conditions (Abdelrahman et al. 1995; Fam et al. 1997). Extensive studies on bond and transfer length have also been conducted. At the Royal Military College of Canada (RMC), work has been done on aramid FRP tendons (McKay and Erki 1993), and more recently on carbon FRP tendons. Researchers at Queen's University have been investigating the low temperature and long-term behavior of beams prestressed with CFRP (Bryan and Green 1996). Additionally, the possibility of using CFRP rods to prestress bridge deck slabs was investigated (Brimacombe et al. 1996), and work on the transfer length of beams prestressed with carbon FRP was conducted (Soudki et al. 1997). Partially prestressed, partially bonded FRP tendons have been investigated (Rizkalla et al. 1997). Noncorrosive wedge-type anchorages for FRP tendons have

been developed at the University of Calgary (Sayed-Ahmed and Shrive 1998; Campbell et al. 2000; Shaheen 2004). At the University of Sherbrooke, extensive investigations are being conducted into the durability of FRP rods for reinforcing and prestressing concrete, and into the development of a bond-type anchorage (Zhang 2002). The effects of temperature on beams prestressed with FRP tendons have been the focus of research at Concordia University, and applications of unbonded FRP tendons have been considered at the University of Windsor (Salib et al. 1999). Researchers at Carleton University and the University of Waterloo are also investigating applications of FRP prestressing tendons.

The decline in the Japanese economy in the 1990s slowed the Japanese development program and has curtailed the availability of many Japanese products for evaluation and testing in North America. Developments in Japan have been addressed by Fukuyama (1999), and details of some recent projects are available from the Advanced Composites Cables (ACC) Club.

Activities in Europe relating to the use of FRP have been reported by Taerwe and Matthys (1999). Of the projects financially supported by the European community, the BRITE/EURAM project, "Fiber Composite Elements and Techniques as Non-Metallic Reinforcement for Concrete," started November 1991 and ended in 1996. The Universities of Braunschweig and Ghent, together with industrial partners from Germany and The Netherlands, investigated performance characteristics and structural aspects of FRP reinforcement for prestressed and reinforced concrete members. The EUROCRETE project, a pan-European collaborative research program with partners from the United Kingdom, the Netherlands, Switzerland, France, and Norway, began in December 1993 and ended in 1997. This project included material development, research on durability in aggressive environments, determination of structural behavior, and development of design guidance, techno-economic, and feasibility studies. The project included construction of demonstration structures.

1.5—Demonstrations and field applications

During the late 1980s and throughout the 1990s, several demonstration projects have shown the potential of FRP prestressing applications. The Marienfelde Bridge in Berlin, completed in 1988, is the first structure to be built in Germany since 1945 with external unbonded prestressing (Wolff and Miesslerer 1989). It is a two-span, 27.61 m (90.5 ft) and 22.98 m (75.1 ft) continuous double-T section beam providing a pedestrian walkway and a bridle path. Seven external Polystal® tendons, each composed of 19 glass fiber bars, are located between the beam webs. Each tendon has a working load of 600 kN (135 kip), is 7.5 mm (0.3 in.) in diameter, and is covered with a 5 mm (0.2 in.) thick sheathing. Four bars out of a group of 19 in a tendon slipped out of the anchorage during prestressing. The treatment for bar slippage was not very difficult because the external prestressing system readily permitted replacement of the entire tendon, complete with the duct and anchorages, at both ends.



Fig. 1.2—Construction of the FRP prestressed girders for the Taylor Bridge in Headingly, Manitoba, Canada.

The BASF bridge in Ludwigshafen, Germany, is a prestressed roadbridge (Zoch et al. 1991). The bridge girder has width for two lanes, and the total length is 85 m (278 ft). Four CFRP tendons were used in conjunction with 16 conventional steel tendons as internal unbonded post-tensioned reinforcement. Each tendon consisted of 19 carbon fiber-reinforced polymer (CFRP) strands of 12.5 mm (0.5 in) diameter, with a prestressing force of 70 kN (16 kip) applied on each strand. The die-cast/wedge anchorage was chosen for applying prestress by post-tensioning to the bridge girder. All tendons were guided through tubes embedded in the concrete, steel tendon tubes were filled with cement grout after tensioning, while the CFRP tendon tubes were not filled to allow inspection, exchange of tendons, and data collection.

In 1993, a bridge was built in Calgary using FRP pretensioned tendons incorporating fiber optic sensors (Rizkalla and Tadros 1994). This was the first bridge of its kind in Canada and one of the first in the world. A second bridge incorporating FRP prestressing tendons was built at Headingly, Manitoba, in 1997. Figure 1.2 shows the fabrication of the prestressed girders for the Taylor Bridge in Headingly, and Fig. 1.3 shows the completed bridge.

Figures 1.4 and 1.5 show the Bridge Street Bridge in Southfield, Michigan. This bridge was completed in 2001 and is a three-span structure that used bonded and unbonded CFRP tendons in both longitudinal and transverse directions (Grace et al. 2002). The Bridge Street Bridge Deployment Project consists of two parallel, independent bridges (Structure A and Structure B) over the Rouge River in the City of Southfield, Michigan. Both structures are designed to accommodate one traffic lane and incorporate three 15-degree skewed spans. Structure A consists of new substructure and superstructure and incorporates five equally spaced conventional AASHTO-I beams in each of the three spans, with a continuous cast-in-place concrete deck slab. Structure B consists of twelve double T (DT) beams, each prestressed using pretensioned Leadline tendons and post-tensioned, in the longitudinal and transverse directions, using carbon fiber composite cable (CFCC) strands. Details of the construction of the Bridge Street Bridge can be found in the literature (Grace et al. 2002). Bridge Structures A and B were designed



Fig. 1.3—Completed Taylor Bridge in Headingly, Manitoba, Canada.



Fig. 1.5—Completed Bridge Street Bridge (Grace et al. 2002).



Fig. 1.4—Erection of the Bridge Street Bridge, Southfield, Mich. (Courtesy of HRC Consulting Engineers, Inc., Mich.)

for two traffic lanes using the provisions to the extent possible of the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges (sample calculations in Grace and Singh [2003]). The superstructure dead loads for Structure B included the DT beams, composite CFRP-reinforced concrete topping, surfacing mixture, pedestrian sidewalk, barrier wall, and the bridge parapet and railing. Live load design was based on the Michigan MS-23 standard truck loading. This live load condition corresponds to 125% of the Michigan MS-18 (AASHTO HS20-44) standard truck

loading. The live load distribution factor used for design of the DT beams was calculated two different ways, using provisions defined in both the AASHTO Standard and AASHTO LRFD Bridge Design Specifications.

Four demonstration projects, in which FRP pretensioned concrete piles have been driven successfully, have been carried out in the United States. Further details of these projects are given in Chapter 8.

1.6—Definitions

Definitions of terms used in concrete structures are found in “Cement and Concrete Terminology (ACI 116R).” Terms and notation that have specific application to FRP reinforcement and prestressing are defined as follows.

A

AFRP—aramid fiber-reinforced polymer.

alkalinity—the condition of having or containing hydroxyl (OH^-) ions; containing alkaline substances. Note: in concrete, the alkaline environment has a pH above 12.

anchor—in prestressed concrete, to lock the stressed tendon in position so that it will retain its stressed condition.

anchorage—In post-tensioning, a device used to anchor the tendon to the concrete member; in pretensioning, a device used to maintain the elongation of a tendon during the time interval between stressing and release.

anchorage, dead-end—the anchorage at that end of a tendon that is opposite to the jacking end.

B

balanced FRP reinforcement ratio—the reinforcement ratio in a flexural member that causes the ultimate strain of FRP and the ultimate compressive strain of concrete to be simultaneously attained.

bar—a nonprestressed FRP element, made mostly of continuous fibers with nominally rectangular or circular cross section, used to reinforce a structural concrete component; the bar may have a deformed or roughened surface to enhance bonding with concrete.

bond stress—the stress between the concrete and the reinforcing element.

bond stress, average—the force in a reinforcing element divided by the product of the perimeter and the development length of the reinforcing element.

bond, transfer—in pretensioning, the bond stress resulting from the transfer of stress from the tendon to the concrete.

bonded member—a prestressed concrete member in which the tendons are bonded to the concrete either directly or through grouting.

bonded tendon—prestressing tendon that is bonded to concrete either directly or through grouting.

C

camber—a deflection that is intentionally built into a structural element or form to improve appearance or to nullify the deflection of the element under the effects of loads, shrinkage, and creep.

CFRP—carbon fiber-reinforced polymer.

coefficient of thermal expansion—change in linear dimension per unit length.

composite—a combination of one or more materials differing in form or composition on a macroscale. Note: the constituents retain their identities; that is, they do not dissolve or merge completely into one another, although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

concrete clear cover—the least distance from the concrete surface to the nearest surface of embedded prestressing tendon or reinforcement.

creep—the inelastic strain of a material under a sustained load over a period of time.

creep-rupture—the tensile fracture of a material subjected to sustained high stress levels over a period of time.

D

deformability—ratio of deflection parameter of a member at ultimate to the same parameter at cracking.

development length—length of embedded reinforcement required to develop the nominal capacity of a member.

duct—a conduit for post-tensioning tendons.

E

effective depth of section—distance measured from the extreme compression fiber to the centroid of the tensile reinforcement.

effective prestress—stress remaining in prestressing tendons after all losses have occurred.

embedment length—length of embedded reinforcement provided beyond a critical section.

F

fiber, aramid—highly oriented organic fiber derived from polyamide incorporating an aromatic ring structure.

fiber, carbon—fiber produced by the heating and stretching for molecular alignment of organic precursor materials containing a substantial amount of carbon, such as rayon, polyacrylonitrile (PAN), or pitch, in an inert environment.

fiber content—the amount of fiber present in a composite. Note: this usually is expressed as a percentage volume fraction or weight fraction of the composite.

fiber-reinforced polymer (FRP)—composite material consisting of continuous fibers impregnated with a fiber-binding polymer, then molded and hardened in the intended shape.

fiber volume fraction—the ratio of the volume of the fibers to the total volume of the fiber-reinforced composite.

H

harped tendons—tendons that have a trajectory that is bent with respect to the center of gravity axis of the concrete member.

J

jacking force—the temporary force exerted by the device that introduces tension into prestressing tendons.

L

limit states—those conditions of a structure in which it ceases to fulfill the relevant function for which it was designed.

load factor—factor applied to a specified load that, for the limit state under consideration, takes into account the variability of the loads and load patterns, and analysis of their effects.

load, factored—product of a specified load and its load factor.

load, sustained—specified dead load plus that portion of the specified live load expected to act over a period of time sufficient to cause significant long-term deflection.

loss, elastic—in prestressed concrete, the reduction in prestressing load resulting from the elastic shortening of the member.

loss, friction—the stress loss in a prestressing tendon resulting from friction between the tendon and duct or other device during stressing.

loss, shrinkage—reduction of stress in prestressing tendon resulting from shrinkage of concrete.

loss of prestress—the reduction in the prestressing force that results from the combined effects of slip at anchorage, relaxation of stress, frictional loss, and the effects of elastic shortening, creep, and shrinkage of the concrete.

M

matrix—the material that serves to bind the fibers together, transfer loads to the fibers, and protect them against environmental attack and damage due to handling.

P

post-tensioning—a method of prestressing in which the tendons are tensioned after the concrete has hardened.

prestressed concrete—concrete in which the internal stresses have been initially introduced so that the subsequent stresses resulting from dead load and superimposed loads are counteracted to a desired degree; this may be accomplished by post-tensioning or pretensioning.

pretensioning—a method of prestressing in which the tendons are tensioned before the concrete is placed.

pultrusion—a continuous process for manufacturing composites that have a uniform cross-sectional shape; the process consists of pulling a fiber-reinforced material through a resin impregnation bath then through a shaping die where the resin is subsequently cured.

R

relaxation—the loss of tension with time in a stressed tendon maintained at constant length and temperature.

resistance factor—factor applied to a specified material property or to the resistance of a member for the limit state under consideration, which takes into account the variability of dimensions, material properties, workmanship, type of failure, and uncertainty in the prediction of resistance.

S

splitting tensile strength—tensile strength of concrete determined by a concrete cylinder splitting test.

strand—a linear component that constitutes either a part or the whole of a prestressing tendon.

T

tendon—an element such as a wire, bar, rope, a single strand, or an assembly of multiple strands used to impart prestress to a structural component. Note: Distinction is made between strands and tendons. Strands refer, for example, to pultruded FRP rods and tendons to bundled FRP rods stressed by common anchors.

thermoplastic—resin that is not cross-linked, and generally can be remelted and recycled.

thermoset—resin that is formed by cross-linking polymer chains and cannot be melted or recycled because the polymer chains form a three-dimensional network.

tow—an untwisted bundle of continuous fibers.

transfer—act of transferring force in prestressing tendons from jacks or the pretensioned anchorage to the concrete member.

transfer length—the length from the end of the member where the tendon stress is zero, to the point along the tendon where the prestress is fully effective, also called transmission length.

V

vinyl esters—a class of thermosetting resins containing esters of acrylic, methacrylic acids, or both, many of which have been made from epoxy resin.

1.7—Notation

A_p	=	cross-sectional area of FRP tendon, mm ² (in. ²)
A_{pi}	=	cross-sectional area of FRP tendon at level i , mm ² (in. ²)
$A_{p\ int}$	=	area of the internal prestressed reinforcement, mm ² (in. ²)
$A_{p\ tot}$	=	total area of internal and external prestressed reinforcement, mm ² (in. ²)
A_s	=	area of nonprestressed tensile reinforcement, mm ² (in. ²)
A'_s	=	area of nonprestressed compressive reinforcement, mm ² (in. ²)

A_v	=	amount of FRP shear reinforcement within spacing s , mm ² (in. ²)
$A_{v,min}$	=	minimum amount of FRP shear reinforcement within spacing s , mm ² (in. ²)
a	=	depth of the equivalent compression block, mm (in.)
b	=	width of compression face of member, mm (in.)
b_w	=	width of web (width of a rectangular cross section), mm (in.)
c	=	depth of neutral axis, mm (in.)
c_u	=	depth of neutral axis at ultimate, mm (in.)
DI	=	deformability index
d	=	depth to the FRP tendon (distance from extreme compression fiber to centroid of tension reinforcement), mm (in.)
d_b	=	diameter of reinforcing bar, mm (in.)
d_e	=	effective depth, mm (in.)
d_i	=	depth to the FRP tendon in layer i , mm (in.)
d_p	=	depth from the concrete top fiber to the centroid of the prestressing tendon, mm (in.)
d_{pu}	=	depth of the external prestressing tendons at ultimate limit state, mm (in.)
E_c	=	modulus of elasticity of concrete, MPa (psi)
E_f	=	modulus of elasticity of the fibers, MPa (psi)
E_p	=	modulus of elasticity of the prestressed tendon, MPa (psi)
E_r	=	elastic modulus of the resin, MPa (psi)
e_{eff}	=	effective eccentricity, mm (in.)
f	=	maximum stress in tendon due to combined axial load and harping, MPa (psi)
f_c	=	concrete stress in the extreme compression fiber, MPa (psi)
f'_c	=	specified compressive strength of concrete, MPa (psi)
f'_{ci}	=	compressive strength of concrete at time of initial prestress, MPa (psi)
f_{fb}	=	stress in the bent FRP stirrup, MPa (psi)
f_{fu}	=	ultimate tensile strength of the FRP stirrup, MPa (psi)
f_h	=	stress in tendon induced by harping, MPa (psi)
f_i	=	FRP stress in tendon layer i , MPa (psi)
f_m	=	stress increase in bottom layer of FRP tendons due to flexure, MPa (psi)
f_p	=	tendon stress, MPa (psi)
f_{pe}	=	effective stress in tendon (after allowance for all prestress losses), MPa (psi)
f_{pu}	=	design ultimate tensile strength of prestressed FRP tendon and anchorage system, MPa (psi)
f_y	=	yield strength of nonprestressed tensile reinforcement, MPa (psi)
f'_y	=	yield strength of nonprestressed compressive reinforcement, MPa (psi)
h_f	=	depth of the flange in T-section, mm (in.)
I_{cr}	=	cracked moment of inertia, mm ⁴ (in. ⁴)
I_e	=	effective moment of inertia, mm ⁴ (in. ⁴)
I_g	=	gross moment of inertia, mm ⁴ (in. ⁴)
k	=	ratio of neutral axis depth to FRP tendon depth
k_b	=	bond correction factor

k_u	= ratio of neutral axis depth to FRP tendon depth for an over-reinforced section	$\Delta\epsilon_p$	= change in strain in prestressed tendon due to flexure
L	= effective span of beam, length of the prestressing tendon between anchorages, mm (in.)	ϵ_{cp}	= average strain in concrete at centroid of the tendon
L_d	= development length, mm (in.)	ϵ_{cu}	= ultimate strain in concrete in compression
L_{fb}	= flexural bond development length, mm (in.)	ϵ_d	= additional strain in tendon that causes the extreme precompressed fiber to reach zero strain (decompression)
L_t	= transfer length, mm (in.)	ϵ_f	= strain available in tendon for flexure after decompression
l_{tffh}	= tail length of the FRP stirrup, mm (in.)	ϵ_p	= tendon strain
M	= unfactored live load moment, N-mm (in.-lb)	ϵ_{pe}	= effective strain in the FRP tendon after all losses
M_a	= maximum moment in a member at which the deflection is being computed, N-mm (in.-lb)	ϵ_{pi}	= initial elastic strain in FRP tendon
M_{cr}	= cracking moment, N-mm (in.-lb)	ϵ_{pr}	= loss of strain capacity due to sustained loads
M_n	= nominal moment capacity, N-mm (in.-lb)	ϵ_{ps}	= strain in the FRP tendon at service
m	= number of layers of tendons	ϵ_{pu}	= ultimate tensile strain in the prestressed FRP tendons
n	= modular ratio = E_f/E_c	ϕ	= strength reduction factor
n_r	= modular ratio of the resin = E_r/E_f	ϕ_{bend}	= strength reduction for bent stirrup
P_j	= jacking load, N (lbf)	λ	= material constant
R	= radius of curvature of the harping saddle (radius of saddle), mm (in.)	ρ	= reinforcement ratio
r	= radius of the bend of the FRP stirrup or radius of FRP tendon, mm (in.)	ρ_b	= balanced reinforcement ratio
REL	= relaxation losses, %	ρ_i	= reinforcement ratio for reinforcement at level i
R_d	= depth reduction factor, %	Ω	= strain reduction coefficient
R_f	= relaxation component due to relaxation of the fibers, %	Ω_u	= strain reduction coefficient at ultimate
R_p	= relaxation component due to the relaxation of the polymer matrix	ξ	= ratio of effective stress to ultimate tensile strength
R_s	= relaxation component due to straightening of the fibers	ψ_i	= ratio of depth of tendon layer i to depth of bottom tendon layer
R_t	= radius of the tendon, mm (in.)		
S_d	= spacing of the deviators, mm		
s	= stirrup spacing or pitch of continuous spirals, mm (in.)		
y_{cr}	= distance from the extreme compression fiber to the neutral axis of the cracked section, mm (in.)		
y_{eff}	= distance from the extreme compression fiber to the effective neutral axis, mm (in.)		
V_c	= shear resistance provided by concrete, N (lbf)		
V_{frp}	= shear resistance provided by FRP stirrups, N (lbf)		
V_n	= nominal shear strength of a reinforced concrete cross section, N (lbf)		
V_p	= vertical component of prestressing force, N (lbf)		
V_s	= shear resistance provided by steel stirrups, N (lbf)		
V_u	= factored shear load, N (lbf)		
v_f	= volume of fibers in the tendon		
v_r	= volume of resin in the tendon		
α	= factor used in Eq. (3-24)		
α_{fb}	= factor for the flexural bond length of FRP tendon		
α_t	= factor for the transfer length of FRP tendon		
β_1	= stress-block factor for concrete		
β_b	= factor for softening equivalent moment of inertia		
Δf_p	= change in stress in an unbonded prestressed tendon due to flexure, MPa (psi)		

CHAPTER 2—FRP TENDONS AND ANCHORAGES

2.1—FRP tendon characterization

FRP tendons are produced from a wide variety of fibers, resins, shapes, and sizes. Only aramid and carbon fibers, however, are recommended in this document. Glass fibers have poor resistance to creep under sustained loads and are more susceptible to alkaline degradation than carbon and aramid fibers. An FRP tendon is identified by the type of fiber used to make the tendon. The Japanese have developed a system to define FRP tendons (Table 2.1).

The tendon and anchorage comprise a system. The tendon properties are developed for a specific anchorage. Using an alternative anchorage may not result in the same strength and performance properties of the system.

2.2—Commercial tendons

Properties and characteristics of commercially available tendons are summarized in Table 2.2 and are based on the manufacturer's published data. The trade names of the products are used for clarity and historical perspective. Not all tendons are currently available, and the properties of the tendons are subject to change. Some of these tendons are shown in Fig. 1.1.

2.3—Description of tendons

Arapree®—Arapree® was a combined development by AKZO Chemicals and Hollandse Beton Groep in The

Netherlands. The manufacturing rights have been transferred to Sireg S.P.A., an Italian company. Arapree® consists of aramid (Twaron®) fibers embedded in epoxy resin. Two types of cross section are available in the marketplace: rectangular and circular. The former is easier to grip with a wedge-type anchorage (Gerritse and Werner 1988).

The anchorage developed for Arapree®, both flat and round rod types, consists of a tapered metal sleeve into which the tendon is either grouted (post-tensioning application) or clamped between two wedges. The wedge anchorage, designed primarily for temporary use, is comprised of a steel sleeve and two semicylindrical tapered wedges made of Polyamide PA6. The outer surface of the wedges and the inner surface of the metal socket are smooth and noncoated. The inner surface of the wedge, which holds the tendon, is similarly smooth, and gripping of the tendon relies solely on the frictional resistance provided by the plastic.

FiBRA—Mitsui Construction Company of Japan produces an FRP rod known as FiBRA. Braiding of fiber tows, followed by epoxy resin impregnation and curing, form the

rod. Aramid and carbon fibers have been used, with aramid being the most common. Small variations in the manufacturing process produce two types of rod: rigid and flexible. Rigid rods are used for concrete reinforcement, whereas flexible rods, which can be coiled, are used as prestressing tendons (Tamura, Kanda, and Tsuji 1993).

FiBRA has two different types of anchorage: a resin-potted anchorage used for single-tendon anchoring and a wedge anchorage for either single- or multiple-tendon anchoring. This wedge anchorage is made of four steel wedges (held together by an O-ring) that slip inside a steel sleeve with a conical interior surface. Grit is applied to the inner surface of the wedges. The exterior surface of the wedges and the interior surface of the steel sleeve are coated with a dry lubricant to assist in seating and removal of the anchorage.

Technora®—Technora® tendon is an aramid product jointly developed by Sumitomo Construction Company and Teijin Corporation, both of Japan. Technora® is a spirally wound pultruded tendon impregnated with a vinyl ester resin (Noritake et al. 1993). Manufacturing of a spirally wound tendon begins with pultruding the impregnated straight fiber bundles through an unheated die. Identical fiber bundles are spirally wound around the tendon to produce a deformed surface. Longitudinal fiber bundles are added to the outer surface before a second spiral winding is added. The product is then cured in an oven.

Technora® tendons employ either wedge-type or potted-type anchorages. Anchorages for single rod tendons or multiple rod tendons, numbering from three to 19 rods, are

Table 2.1—Fiber identification

Fiber type	Identification
Aramid fiber	A
Carbon fiber	C
Multiple fibers	*

*In a tendon using multiple fibers, the first letter of the two fibers making up the material will be used with the dominant fiber going first (for example, CA for carbon/aramid composite with carbon having the larger volume).

Table 2.2—Properties of FRP tendons (compiled from various references)

Property	AFRP				CFRP	
	Arapree®	FiBRA	Technora®	Parafil®	Leadline™	CFCC
Fiber	Twaron	Kevlar49	Technora	Kevlar49	Carbon	Carbon
Resin	Epoxy	Epoxy	Vinyl ester	—	Epoxy	Epoxy
Fiber volume ratio	0.45	0.65	0.65	—	0.65	0.65
Density, g/cm ³	1.25	1.28	1.3	1.44	1.53	1.5
Longitudinal tensile strength, GPa	1.2 to 1.5	1.25 to 1.4	1.7 to 2.1	1.2 to 1.9	2.25 to 2.55	1.8 to 2.1
Transverse tensile strength, MPa	—	30	—	—	57	—
Longitudinal modulus, GPa	62 to 64	65 to 70	54	120 to 130	142 to 150	137
Transverse modulus, GPa	—	5.5	—	—	10.3	—
In-plane shear strength, MPa	—	4.9	—	—	71	—
In-plane shear modulus, GPa	—	2.2	—	—	7.2	—
Major Poisson's ratio	0.38	0.34 to 0.6*	0.35	—	0.27	—
Minor Poisson's ratio	—	0.02	—	—	0.02	—
Bond strength, MPa	7.7	10 to 13	10 to 16	—	4 to 20	7 to 11
Maximum longitudinal strain, %	2.4	2.0 to 3.7	3.7 to 3.8	1.5 to 1.7	1.3 to 1.5	1.57
Maximum transverse strain, %	—	—	—	—	0.6	—
Longitudinal compressive strength, MPa	—	335	—	—	1440	—
Transverse compressive strength, MPa	—	158	—	—	228	—
Longitudinal thermal expansion coefficient/°C	-2×10^{-6}	-2×10^{-6}	-3×10^{-6}	—	-0.9×10^{-6}	0.5×10^{-6}
Transverse thermal expansion coefficient/°C	50×10^{-6}	60×10^{-6}	—	—	27×10^{-6}	21×10^{-6}
Relaxation ratio at room temperature, % loss from jacking stress	11 to 14	12 at 103 h	8 to 13 at 103 h	6 to 9 at 105 h	2 to 3	0.5 to 1 at 102 h

*Pseudo Poisson's ratio due to structure of tendon.

Notes: A "—" indicates that information is not available or is not applicable. 1 MPa = 145 psi; 1 GPa = 145 ksi; 1 g/cm³ = 62.4 lb/ft³; and 1°C = 1.8/°F.